LISA

Beyond Einstein: From the Big Bang to Black Holes

# LISA Mission Tutorial

Robin T. Stebbins
U.S. Project Scientist

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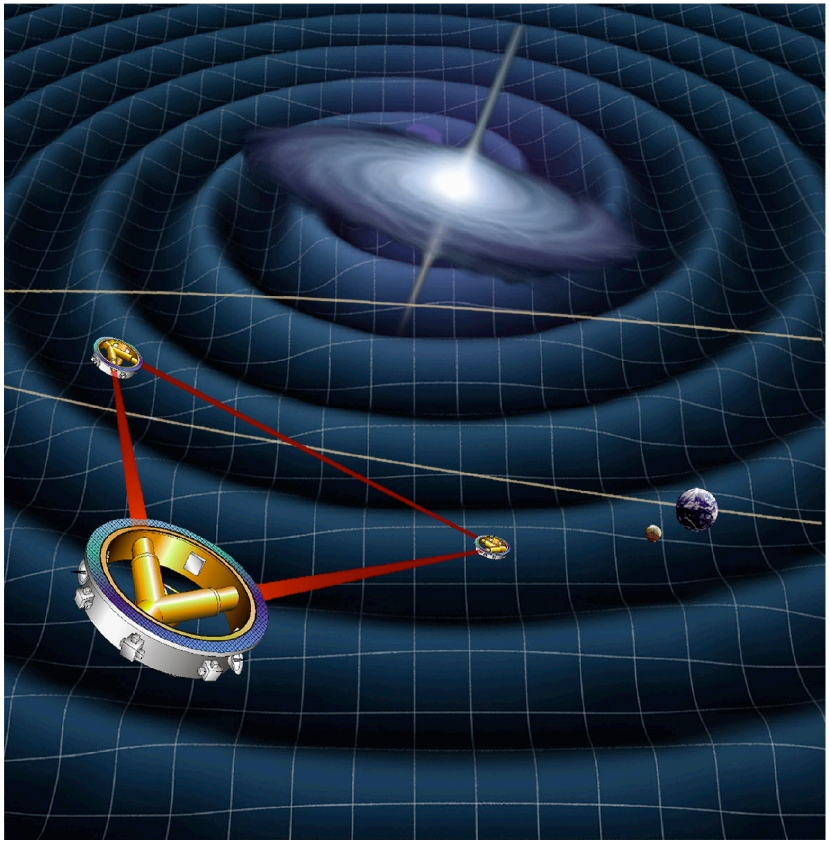
GSFC - JPL

# Outline

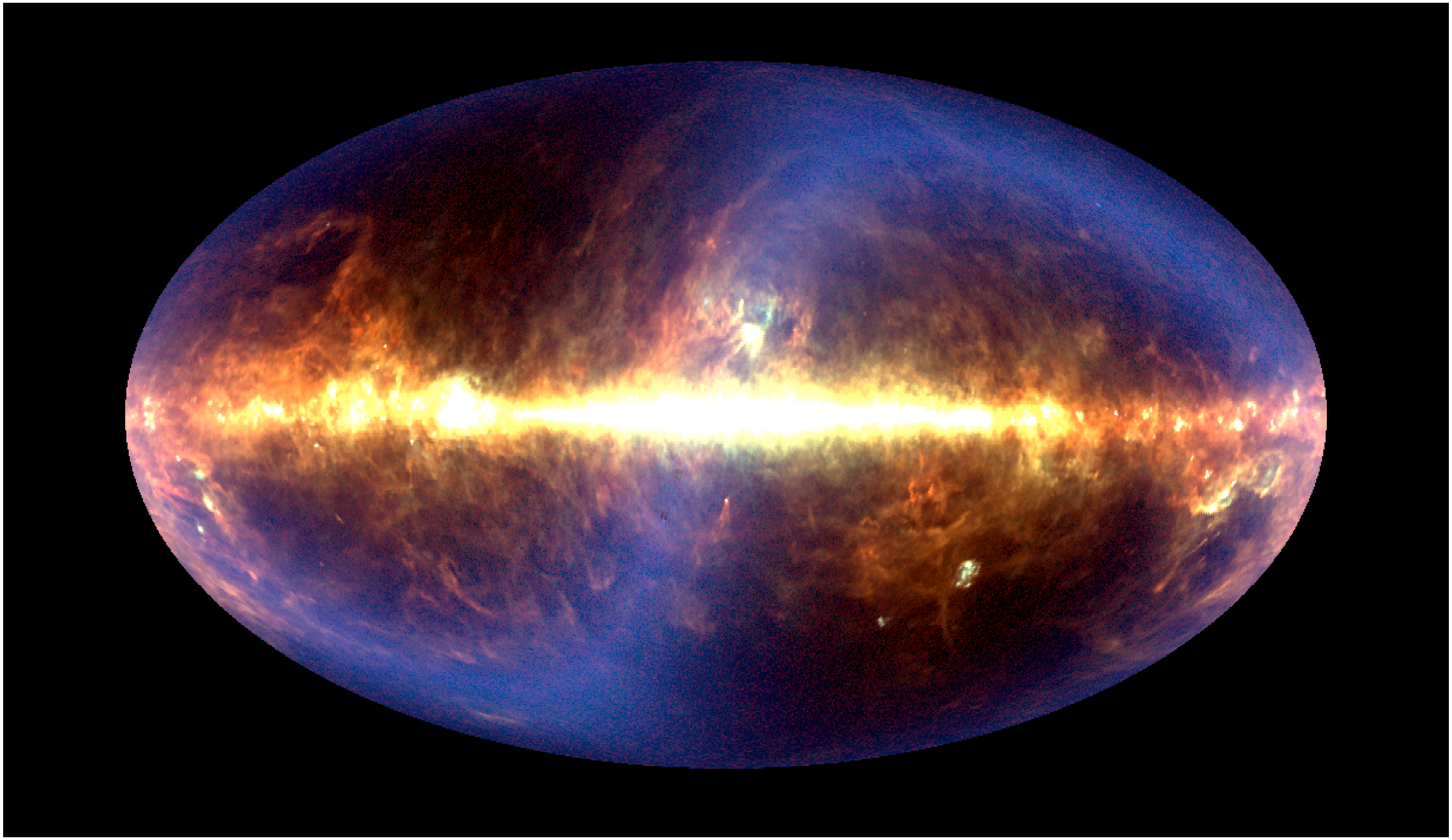
- Overview
- Science
  - Astrophysics in Scott Hughes's Astrophysics Tutorial
- Mission Concept
- Top Level Architecture
- Character of the Data
  - Data analysis in Alberto Vecchio's Data Analysis Tutorial

# LISA Overview



- The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector.
- The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in a triangular formation.
- Space-time strains induced by gravitational waves are detected by measuring changes in the separation of fiducial masses with laser interferometry.
- LISA is expected to detect signals from merging supermassive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact objects in the Milky Way and possibly backgrounds of cosmological origin.

# Science



# Gravitational Waves

- Gravitational waves are propagating distortions in space-time. They appears as a strain - fractional length change - in space-time.
- Never directly detected. Existence of gravitational waves is demonstrated by binary pulsars (e.g., Hulse-Taylor).
- Properties
  - A transmitter consists of accelerating masses, a time variation of its multipole moments. No dipole, quadrupole is lowest possible.
  - GW interferometers measure changes in the separations of a ‘proof’ mass array. GW interferometers detect amplitude, not energy.
- Gravity is weak - strains from expected sources are ~$10^{-21}$.
  - The most precise measurement systems measure displacement, so measuring over long baselines gives the most displacement for a given strain. This leads to interferometry in space.
  - Proof masses must be isolated from disturbances that give comparable motions.
- We frequently characterize gravitational waves and noise by their ***amplitude*** spectral density. Strain ASD has units of ‘per root Hertz.’

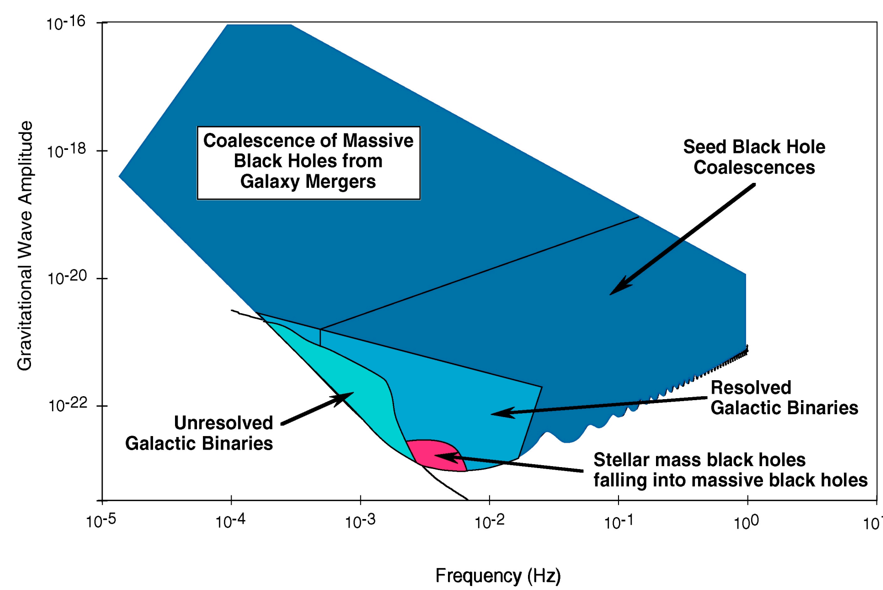
# The Gravitational Wave Sky

- The nature of gravitational wave sources:
  - Very close binary systems of compact objects (white dwarfs, neutron stars, black holes of all sizes)
  - The most violent events in the Universe (visible to z~30)
  - Often shrouded from electromagnetic observation.
- What can be learned from observing these sources:
  - How compact objects - particularly supermassive and intermediate-mass black holes - formed and interacted
  - How proto-galactic structures and dark matter halos formed in the early Universe and what the later merger history of galaxies is
  - How well General Relativity accounts for extreme gravity
  - What is the stellar environment in the immediate vicinity of supermassive black holes in galactic cores
  - What are the demographics of compact objects
  - Is there unexpected physics in the very early Universe

# *Why a gravitational wave antenna in space?*

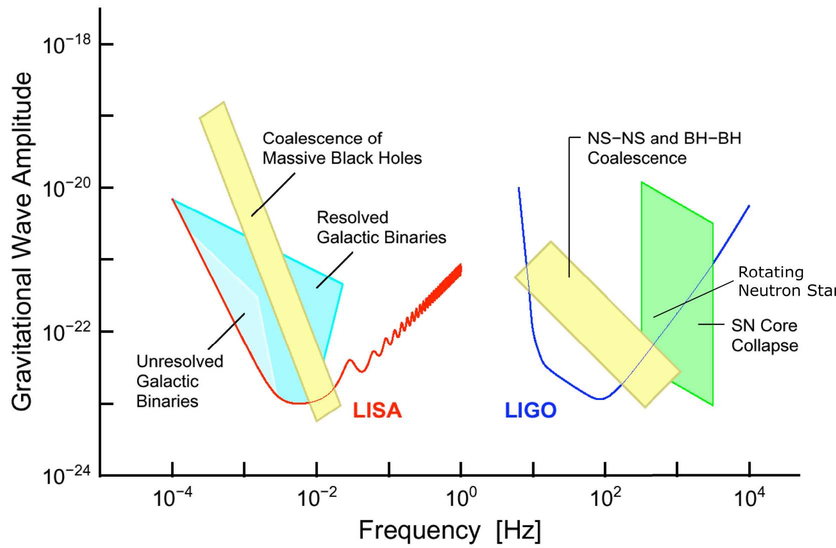
- Gravitational waves are very small strains in space-time.
- Strain is a fractional change in length, $\Delta L/L$. Metrology techniques (i.e. interferometry) measure length changes $\Delta L$. Thus, greater lengths give greater length changes, which are easier to measure.
- The number and variety of potential gravitational wave sources increases toward lower frequencies.
- A quiet environment for gravitational sensors.
- Critical questions:
  - Can one adequately isolate the test masses from spurious forces?
  - Can one adequately measure proof mass motion?
  - Can you do it in space?
  - When, how risky and how costly?

- Supermassive black holes ($10^5$-$10^7$ $M_{\odot}$)
  - Found at centers of most galaxies, may merge when galaxies merge
  - Can trace galaxy formation out to earliest proto-galactic structures
  - 10-10,000 /yr.  Can map dark matter halos and dark energy.
- Intermediate mass black holes ($10^2$-$10^4$ $M_{\odot}$)
  - Can trace hierarchical build up of supermassive black holes and formation of galactic structure
- Close binaries of compact stellar remnants (white dwarves, neutron stars, stellar mass black holes)
  - Known sources
  - >10,000 detectable in Milky Way, remainder a confusion background
- Extreme mass ratio inspirals (10 $M_{\odot}$ spiraling into $10^6$ $M_{\odot}$)
  - Known sources
- Cosmological background
- Other?

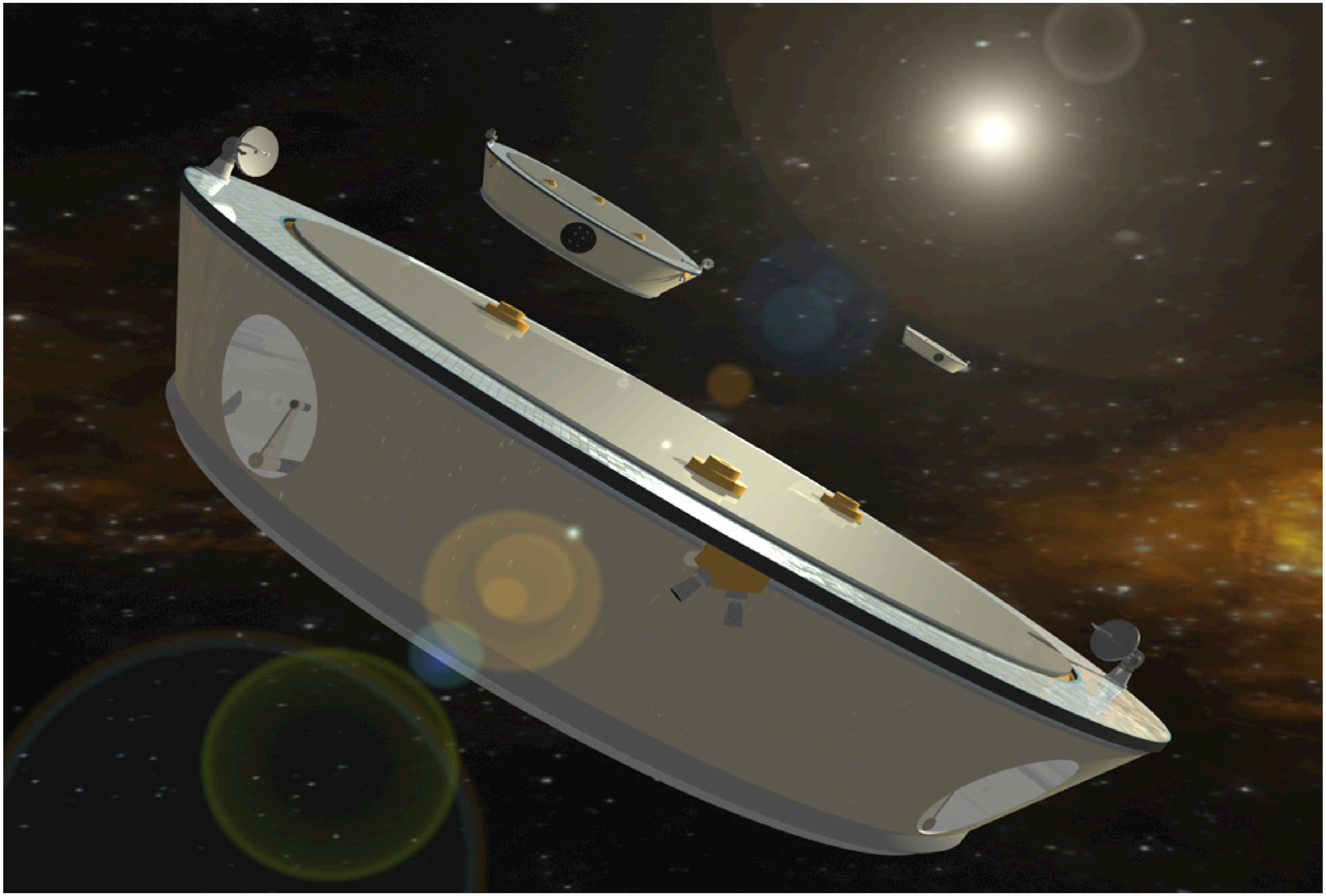


# Other GW Detectors

- Ground-based interferometers
  – LIGO, GEO, Virgo, TAMA
  – Operating band: 50-2000 Hz
- Resonant detectors
  – World-wide network operating for 20 yrs
  – Operating band ~20 Hz near 1 kHz
- Spacecraft tracking
  – Ranging to Cassini and others
  – Operating band $10^{-6}$ - $10^{-7}$Hz



# Mission Concept



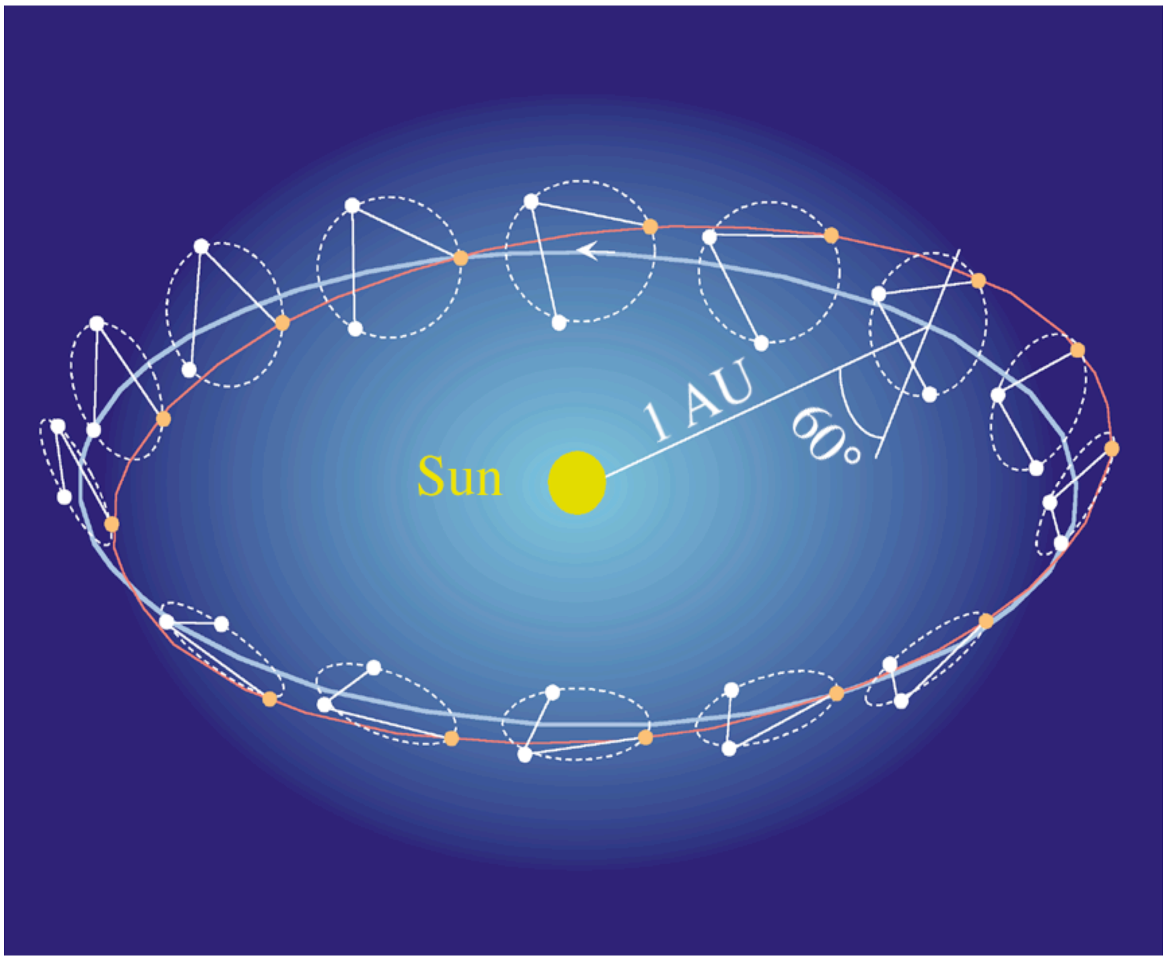
# Mission Concept Overview

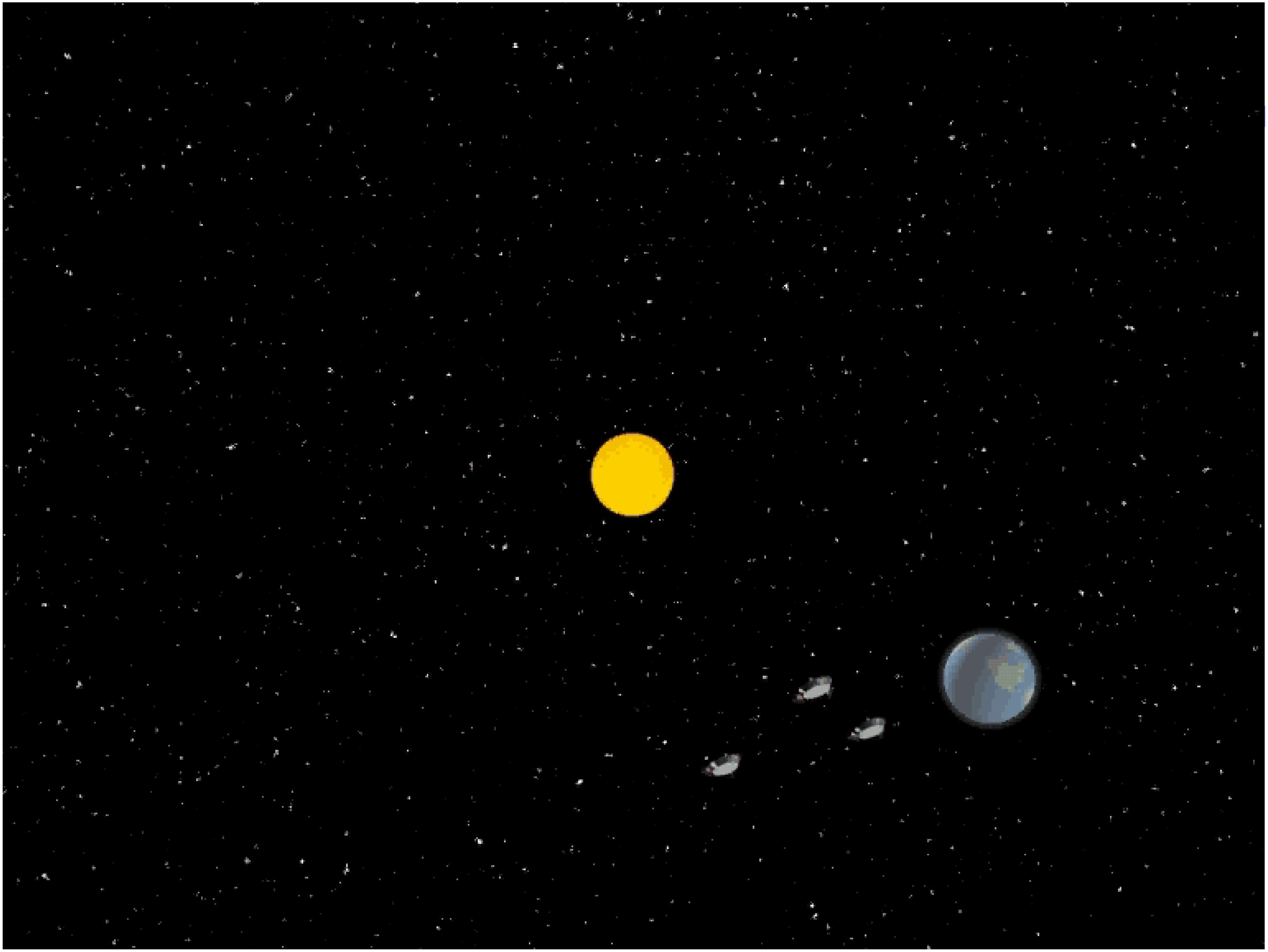


- Measure time-varying strain in space-time by interferometrically monitoring changes in three 5 million kilometer long arms.
- Three spacecraft in a triangular formation orbit the Sun, 20° behind the Earth. A spacecraft at each vertex houses two proof masses and interferometry equipment.
- The three arms:
  - Form an equilateral triangle
  - Are defined by six proof masses, located in pairs at the vertices of the triangle
  - Are monitored interferometrically to achieve a measurement bandwidth from $3 \times 10^{-5}$ to 1 Hz
- The proof masses are protected from disturbances by careful design and "drag-free" operation (i.e., the mass is free-falling, but enclosed and followed by the spacecraft).
- Lasers at each end of each arm operate in a "transponder" mode. Optical path difference changes, laser frequency noise, and clock noise are determined.
- Three arms measure both polarizations of quadrupolar waves. Source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion.

# Orbits

- Orbits are chosen so that the spacecraft passively hold formation.
- Spacecraft have constant solar illumination and benign environment.

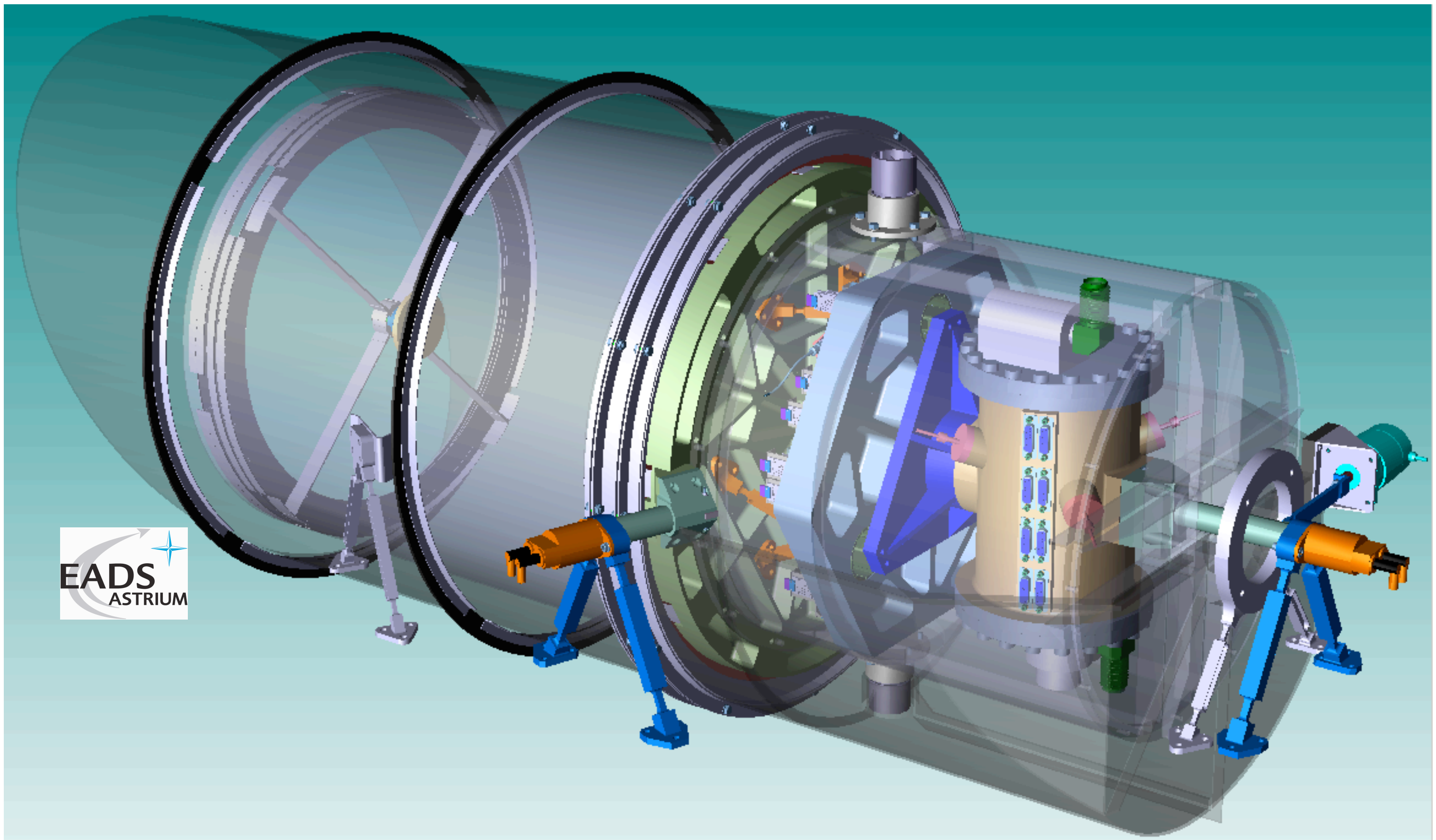




# Mission Sequence

- Launch on Atlas V (531) with positive escape velocity
- Separate three sciencecraft/propulsion module pairs from each other and upper stage of the launch vehicle
- Each propulsion module propels its sciencecraft through the cruise phase (~13 months) , and injects it into final orbit. Sciencecraft are separated from propulsion modules.
- Orbits are trimmed using tracking data, and then allowed to passively evolve over lifetime of the mission.
- Laser pointing and locking is achieved with an acquisition sequence.
- Instrument performance is tuned up and characterized during commissioning phase.
- Sciencecraft operate in a single science mode with high duty cycle.
- Ground contact through DSN every other day.
- Inter-spacecraft communications through modulations on the science beam.

# Instrument Architecture

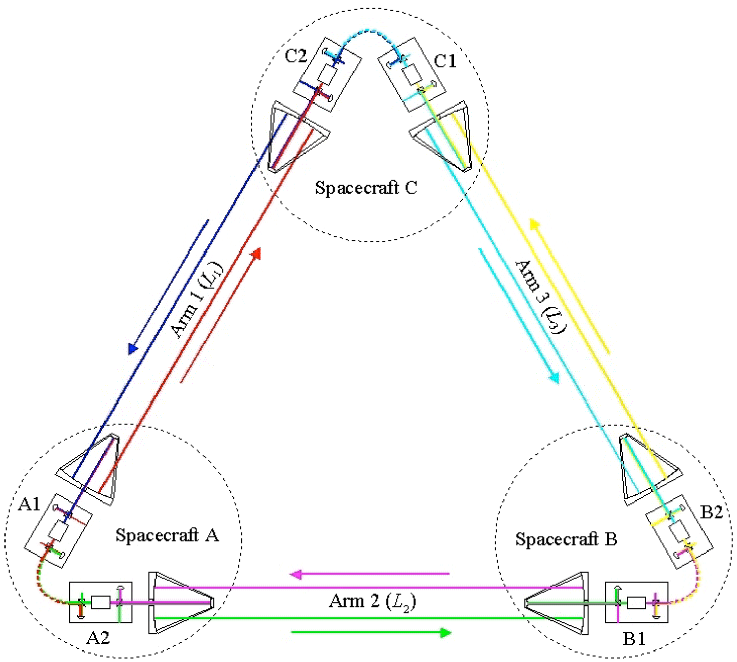


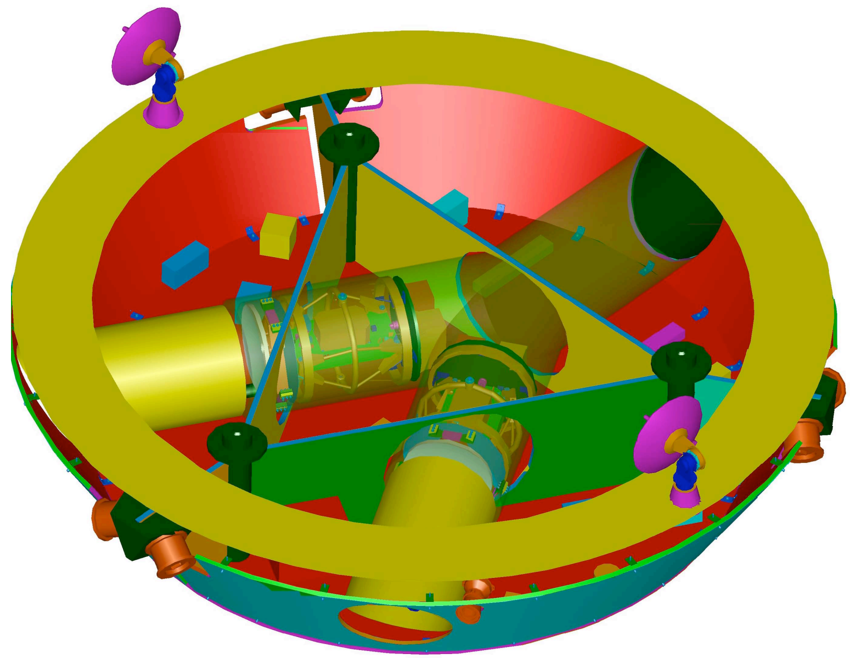
# Instrument Concept



- Six free-falling proof masses define the measured lengths, an interferometric ranging system measures changes in their separation.
- Disturbance Reduction System (DRS)
  - Proof masses
  - Enclosures with sensing, actuation, charge control, caging
  - Spacecraft and proof mass control systems (19 DOF per spacecraft)
  - Drag-free operation
  - Micronewton thrusters based on liquid metal ion propulsion
  - Spacecraft and payload design features to reduce disturbances
- Interferometry Measurement System (IMS)
  - Laser system and stabilization
  - GPS-like range measurement
  - Frequency noise correction

# Sciencecraft



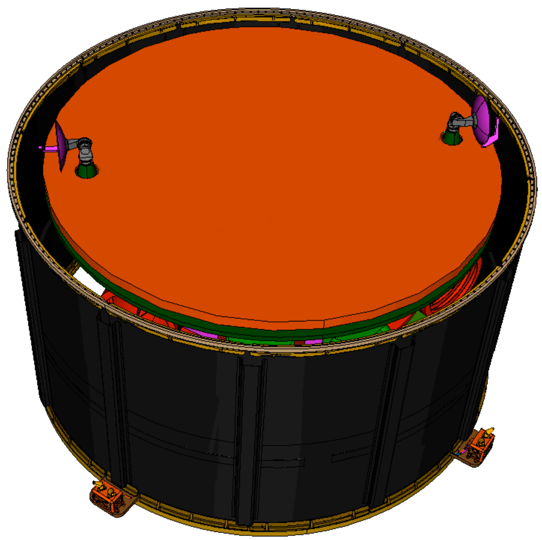



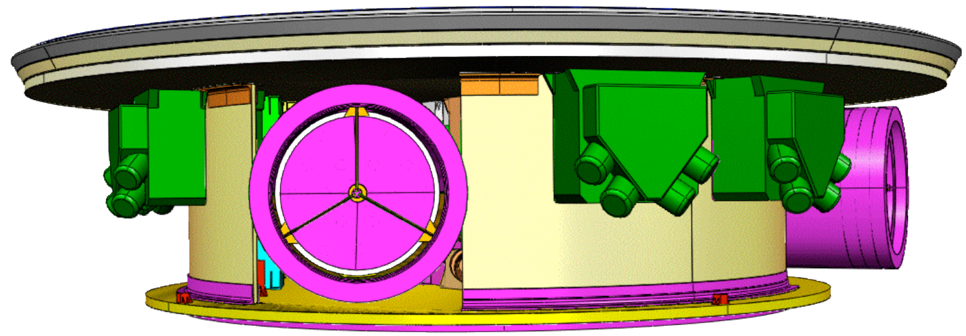
- *Three interacting spacecraft make up the "science instrument"*
- *Multiple combinations of one-way measurements.*

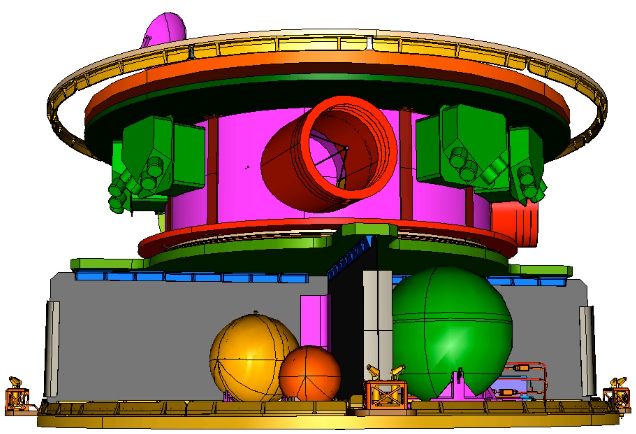
- *Drag-free control protects the proof masses from the ambient environment and reduces the disturbances on the proof masses from the spacecraft.*

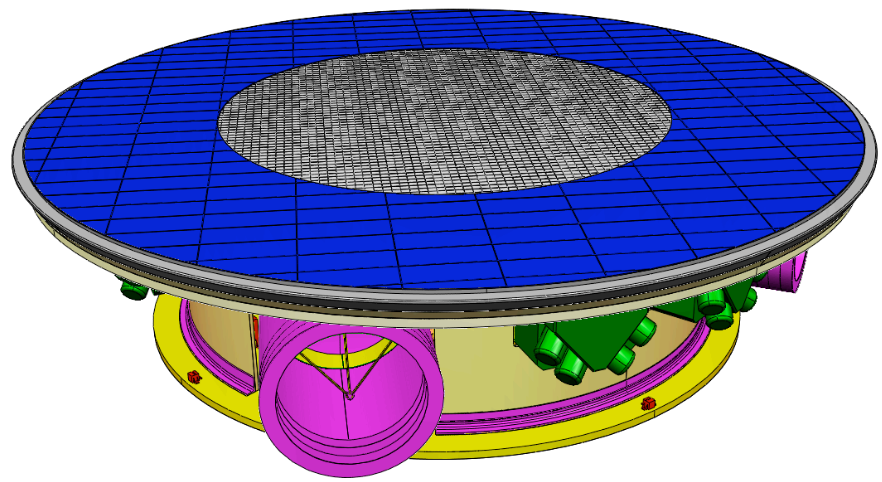
# Sciencecraft







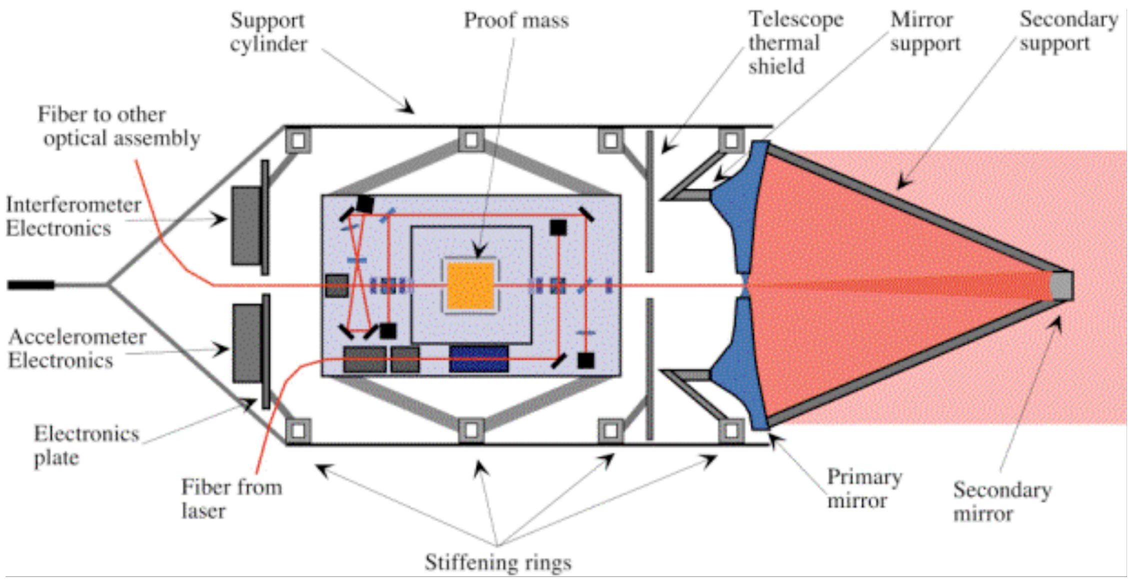




# Distance Measurement Concept

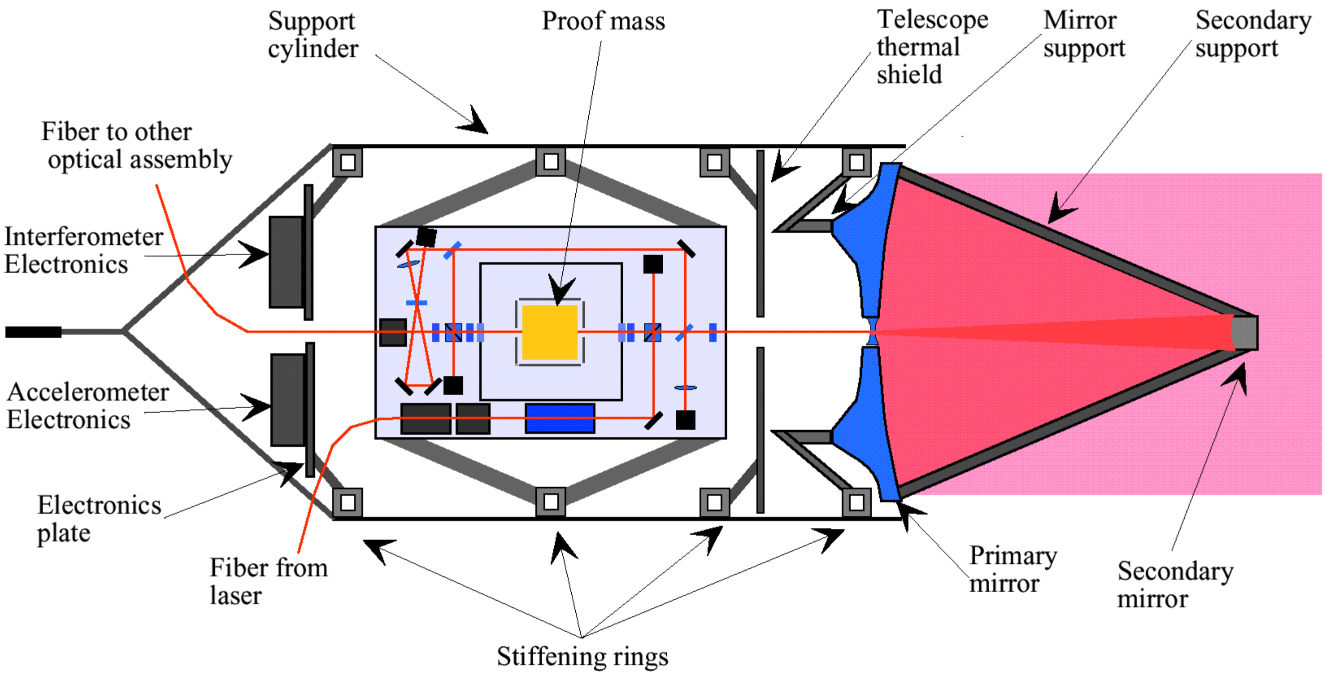
- The distance monitoring system is a continuous ranging system, like spacecraft tracking, using optical frequencies.
- The ranging system senses:
  - Inter-spacecraft doppler motions
  - Temporal variations of laser frequency
  - Time variations of the optical pathlength between proof masses
  - Time variations in the ultra-stable oscillator frequency
- The phasemeter measures the accumulated phase as a function of time.
- The science signal appears as a millihertz phase modulation on a megahertz beat signal.

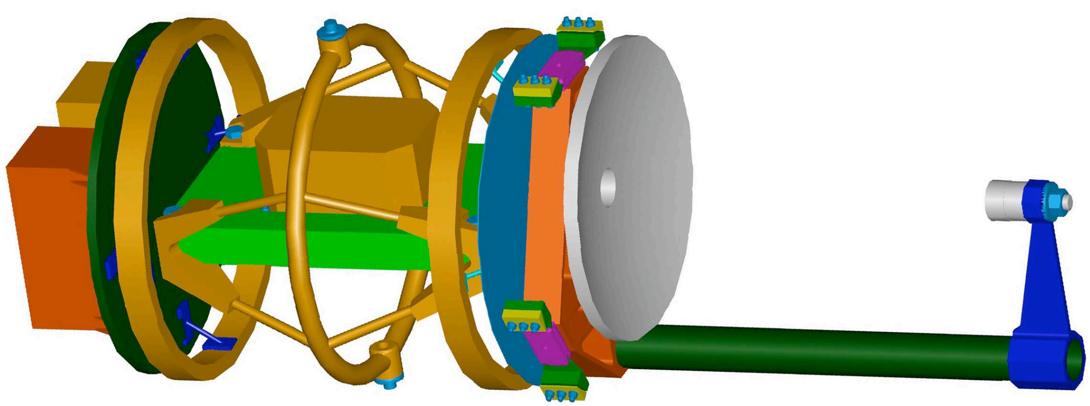
# Interferometry Measurement System




- 30 cm, *f*/1 transmit/receive telescope
- Optical bench with interferometry optics, laser stabilization
- Gravitational reference sensor
- 1.064μ Nd:YAG NPRO master laser, 2 W Yb:YAG fiber amplifier, plus spare
- Fringe tracking and timing electronics, including ultra-stable oscillator
- Fiber link for comparing laser phase between two arms

# Optical Assembly



# Optical Bench

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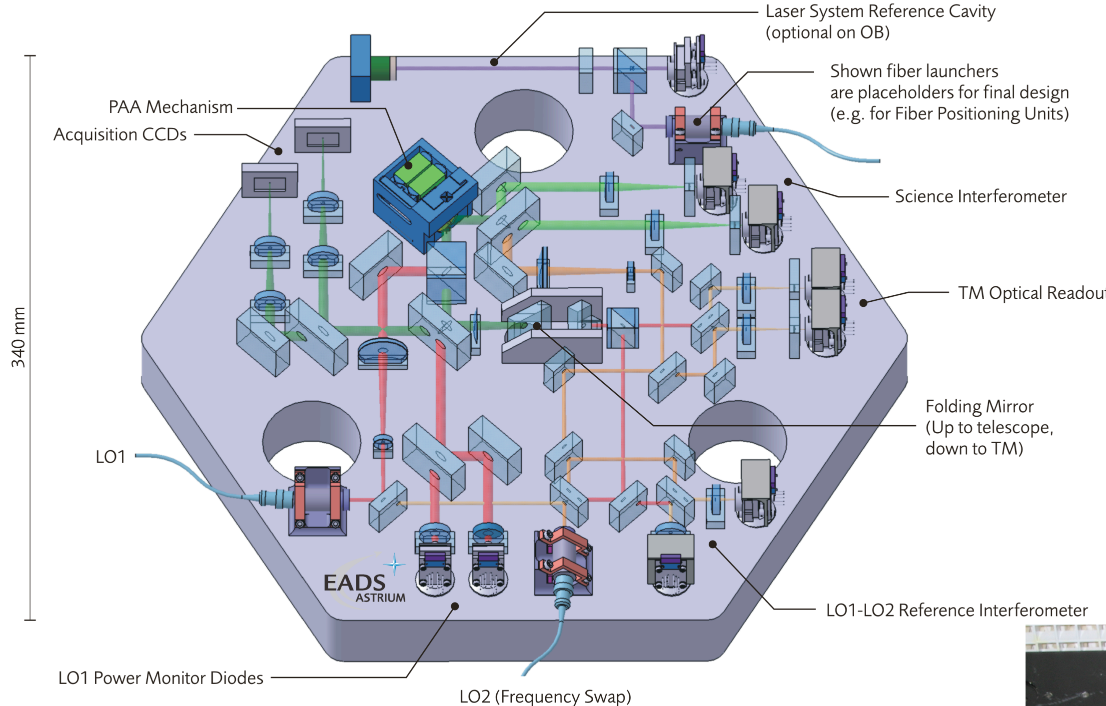
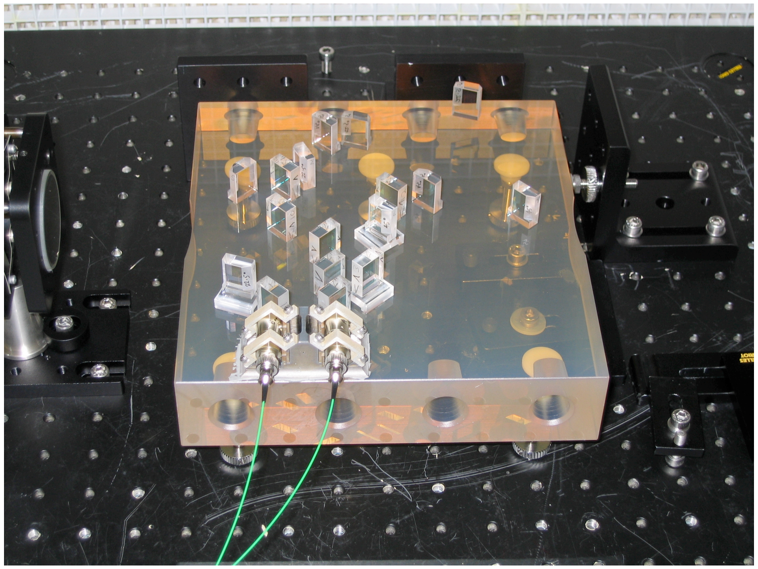
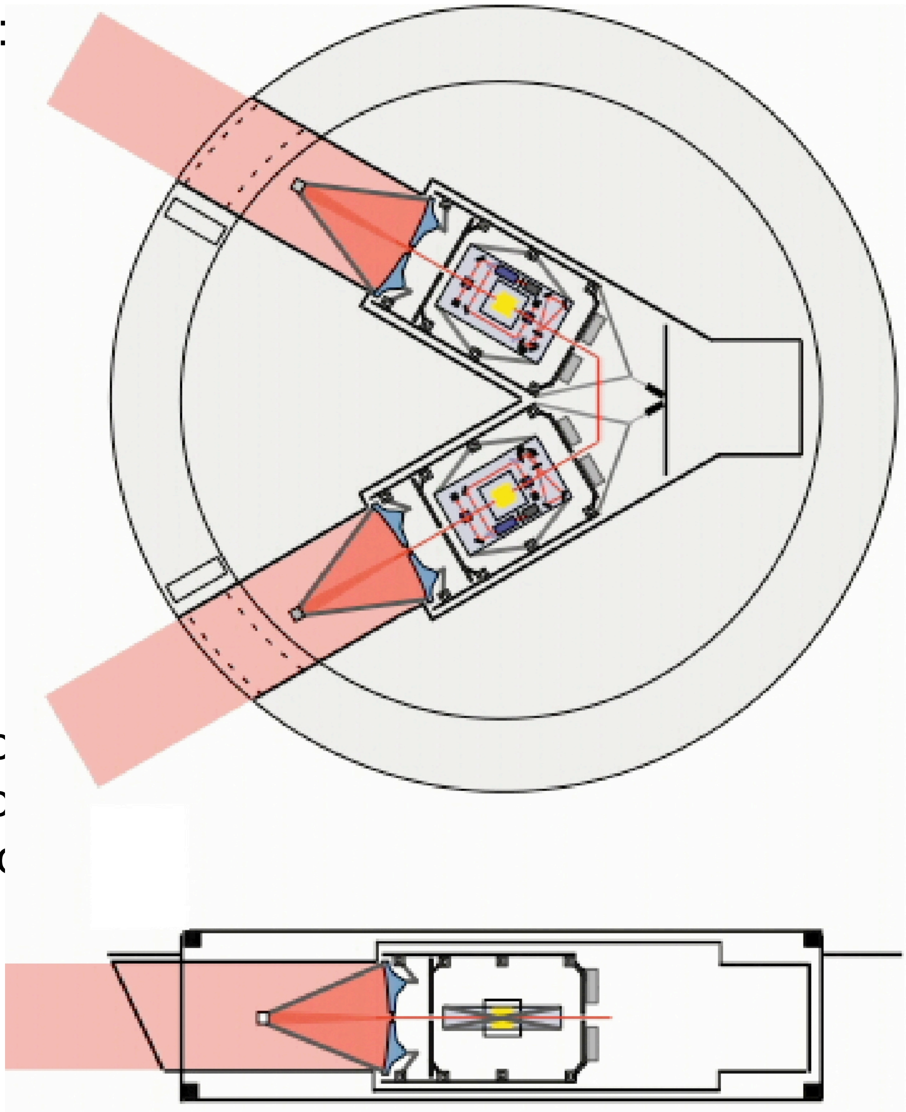


# Disturbance Reduction System

- Gravitational Reference Sensor:
  - Proof mass
  - Electrostatic sensing
  - Electrostatic actuation
  - Charge control
- Microthrusters:
  - Liquid metal ion emitters
  - Neutralizers
- Control Laws
- Integrated spacecraft/payload to hold spurious accelerations belo 3x10$^{-15}$ m/s$^2$/$\sqrt{\text{Hz}}$ at 0.1 mHz and above.



# Character of the Data

- More than 10,000 sources are added at the antenna. The source signals are “detected” in data analysis by searching for their unique waveforms.
- Source direction can be determined
  - Frequency modulation from orbital Doppler shifts
  - Amplitude modulation from moving antenna lobes
  - Phase modulation from time-of-flight across antenna
- The signals
  - 3 Hz sampling of 18 beat signals
  - Require the application of Time Delay Interferometry (TDI) algorithms to remove laser and clock frequency noise
  - Auxiliary ‘sciencekeeping’ data
- The noise
  - Long integration times (~$10^6$ - $10^8$ s)
  - Slowly varying conditions
  - Interruptions
  - Sagnac observables

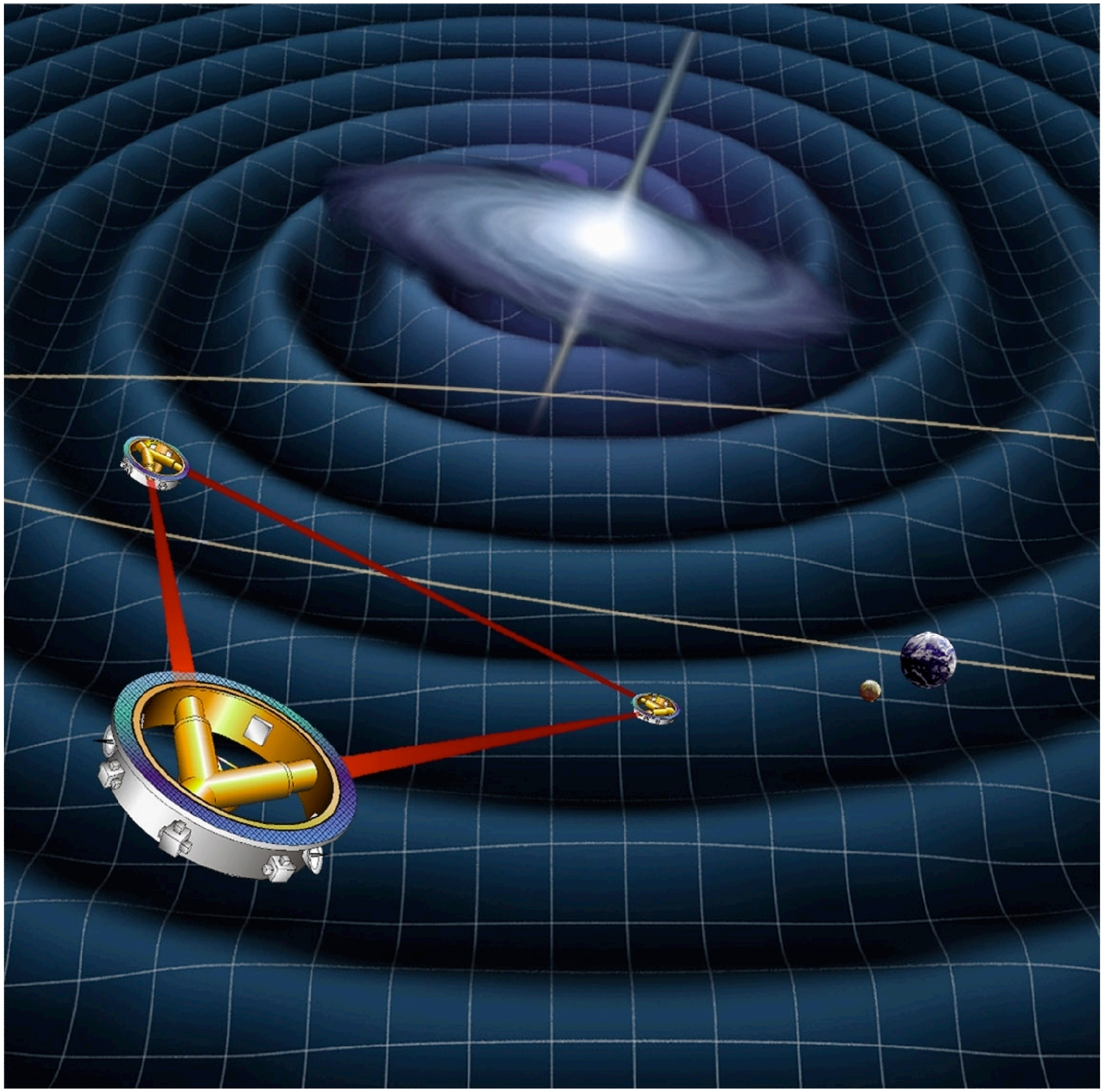
# Summary



- Spectacular science: LISA can
  - Directly detect extreme gravitational interactions of intermediate and massive black holes out to the era of galaxy formation, and beyond.
  - Probe the history of galaxy and proto-galaxy mergers.
  - Test scenarios for the formation of galactic black holes.
  - LISA can probe the environment around galactic engines.
  - Test General Relativity in extremely relativistic situations with great accuracy.
- The mission concept is well-developed.
  - Conceptual design is mature; basic concepts have been stable for 10 yrs.
  - Formulation is very advanced.
  - Design optimizations under study, investigating cost savings.
- The Project is underway:
  - Formulation Phase has started in both U.S. and Europe.
  - Science community is growing.
  - The Project team is established and working.
  - Technology development is progressing.
  - Demonstration flight  is in implementation.

# Backup





# Short LISA History

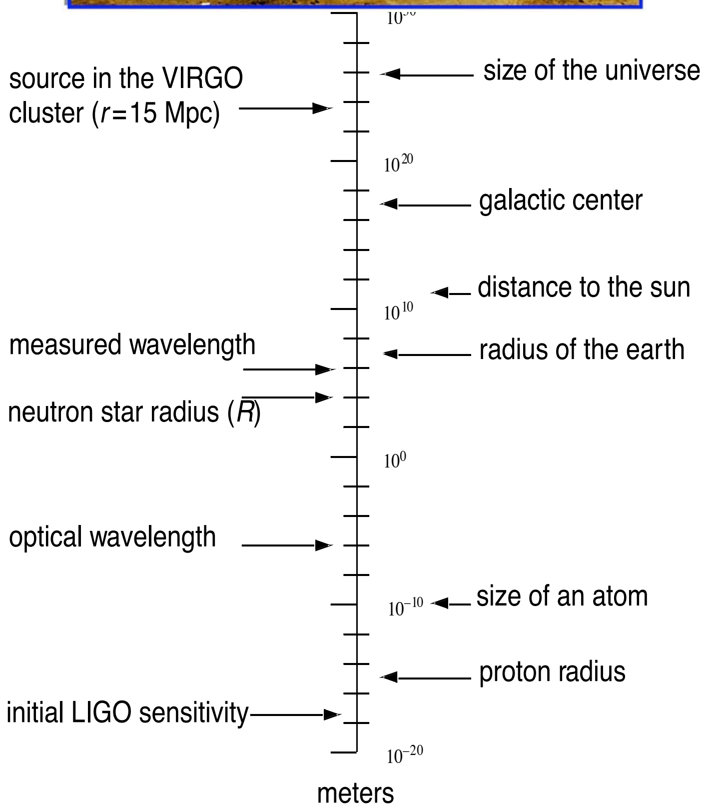
- Foundation paper in 1984 by Bender, Faller, Hall, Hils and Vincent
- Concept developed through
  - Concept studies ‘84-’93
  - ESA Pre-Phase studies ‘93-’98 (*cf.*, PPA2 document)
  - NASA Team-X study ‘98
  - ESA Industrial Phase A Study ‘98-’00 (*cf.*, FTR and STS documents)
  - GSFC Project Office formed in ‘01, technology planning and development commenced.
  - Flight demonstrations (LISA Pathfinder and ST-7) initiated in ‘00-’01
  - NASA Formulation Phase began Oct. ‘04
  - ESA Industrial Formulation Study begun at Astrium/Friedrichshafen Jan. ‘05, finished Phase I in Oct. ‘05
- ***Concept has not significantly changed since PPA2 in 1998.***
- Current focus
  - Architecture definition and refinement, design trade studies
  - Technology development
  - LISA Pathfinder and ST-7

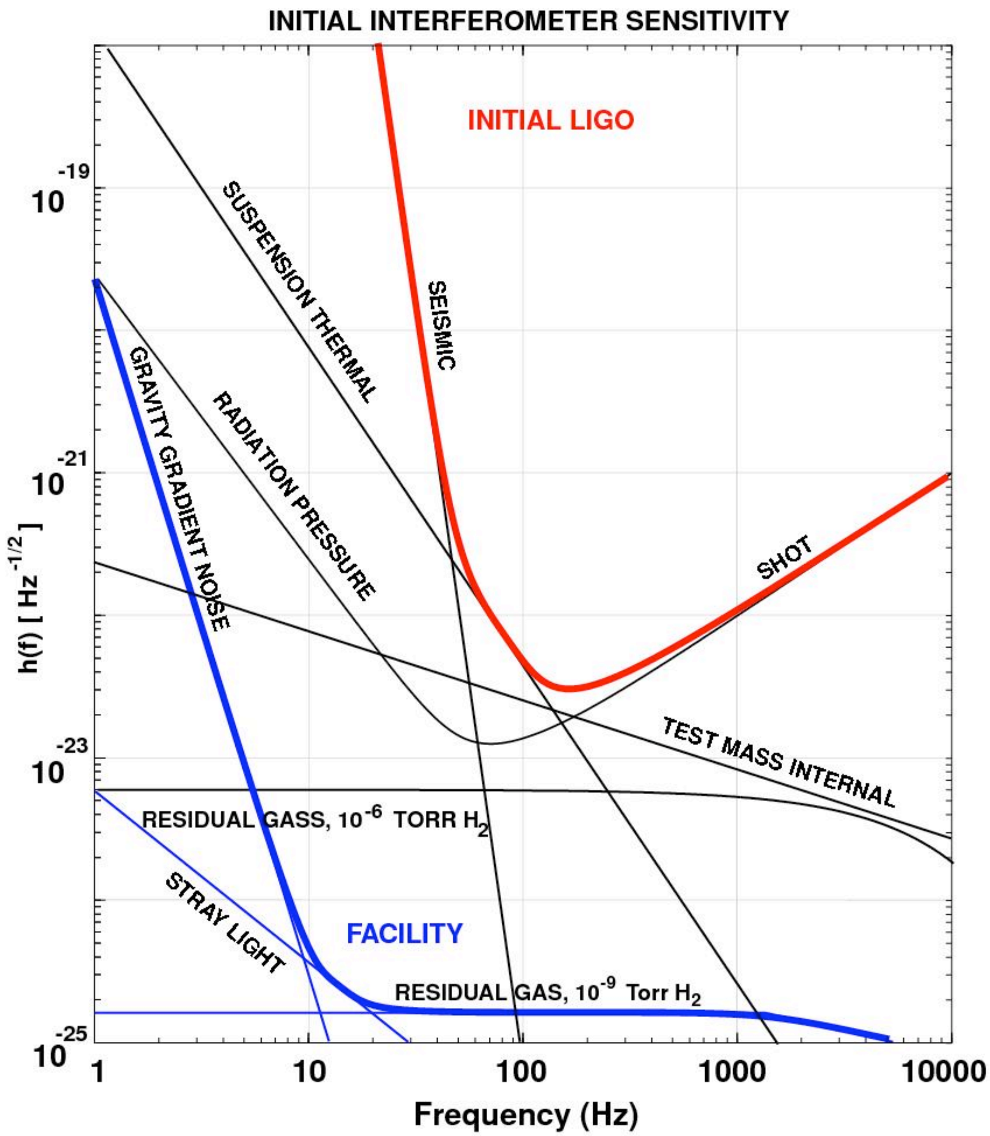
# Current Participants



- NASA
  - GSFC: Project management, system engineering, observatory integration, project scientist
  - JPL: technology development, ST-7/DRS, system engineering, payload components, operations, mission science office
  - Partners
    - University of Colorado at Boulder
    - Caltech
    - Stanford
    - University of Washington
    - University of Florida
    - MIT
    - University of Michigan
    - University of Texas at Austin
    - University of Texas at Brownsville
    - Pennsylvania State University
    - Montana State University (Bozeman and Billings)
    - US Naval Academy
    - University of Maryland
    - And more …
- ESA
  - ESTEC: project management, project scientist, spacecraft, propulsion modules
  - National Agencies (not final): Germany, Italy, UK, France, Netherlands, Spain, Switzerland
  - Institutes and universities
    - University of Hannover
    - Albert Einstein Institute
    - Max Planck Institute for Extraterrestrial Physics
    - University of Trento
    - INFN
    - University of Padova
    - University of Glasgow
    - University of Birmingham
    - Imperial College
    - Rutherford Appleton Laboratory
    - SRON
    - And many, many more …

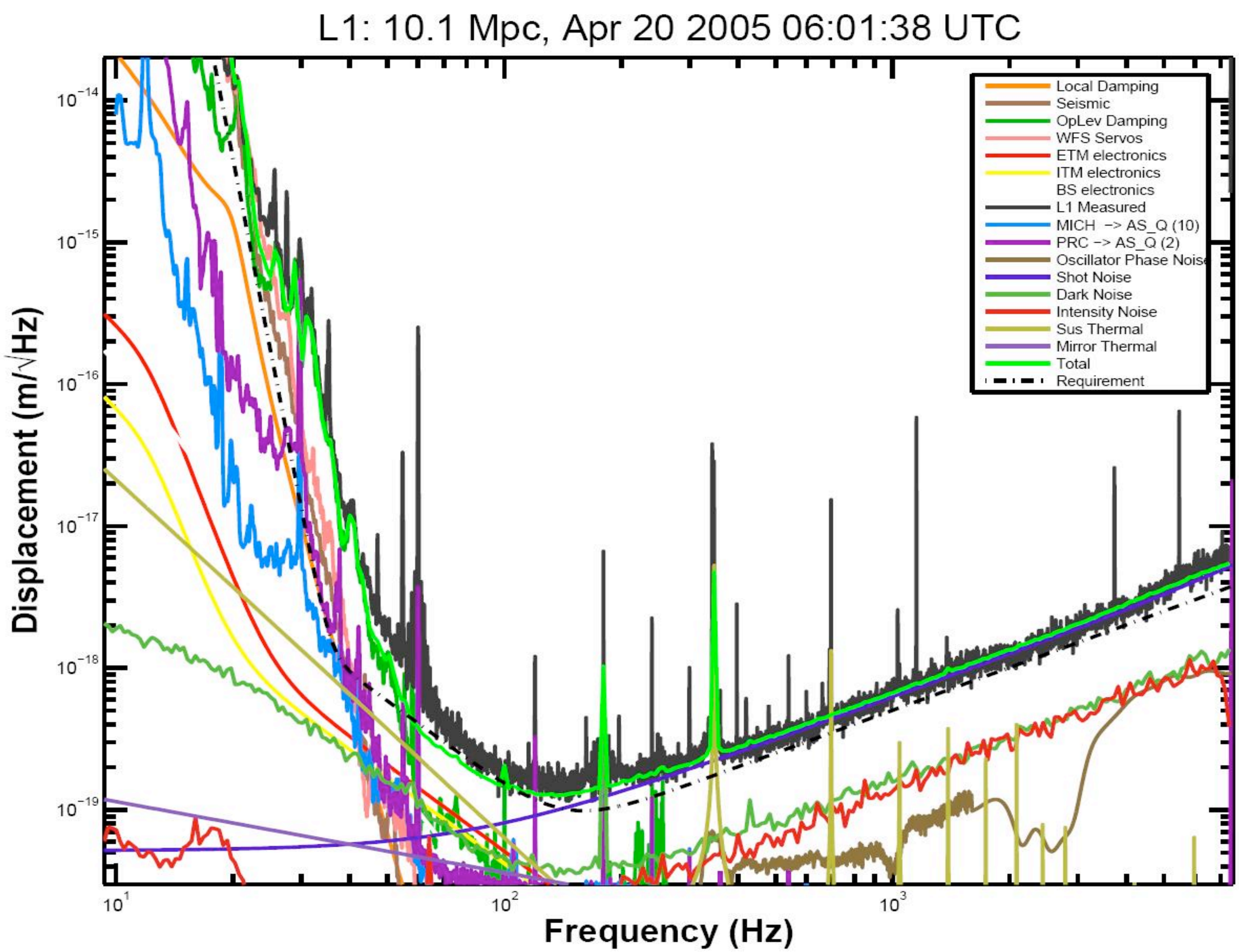
# LIGO Sensitivity



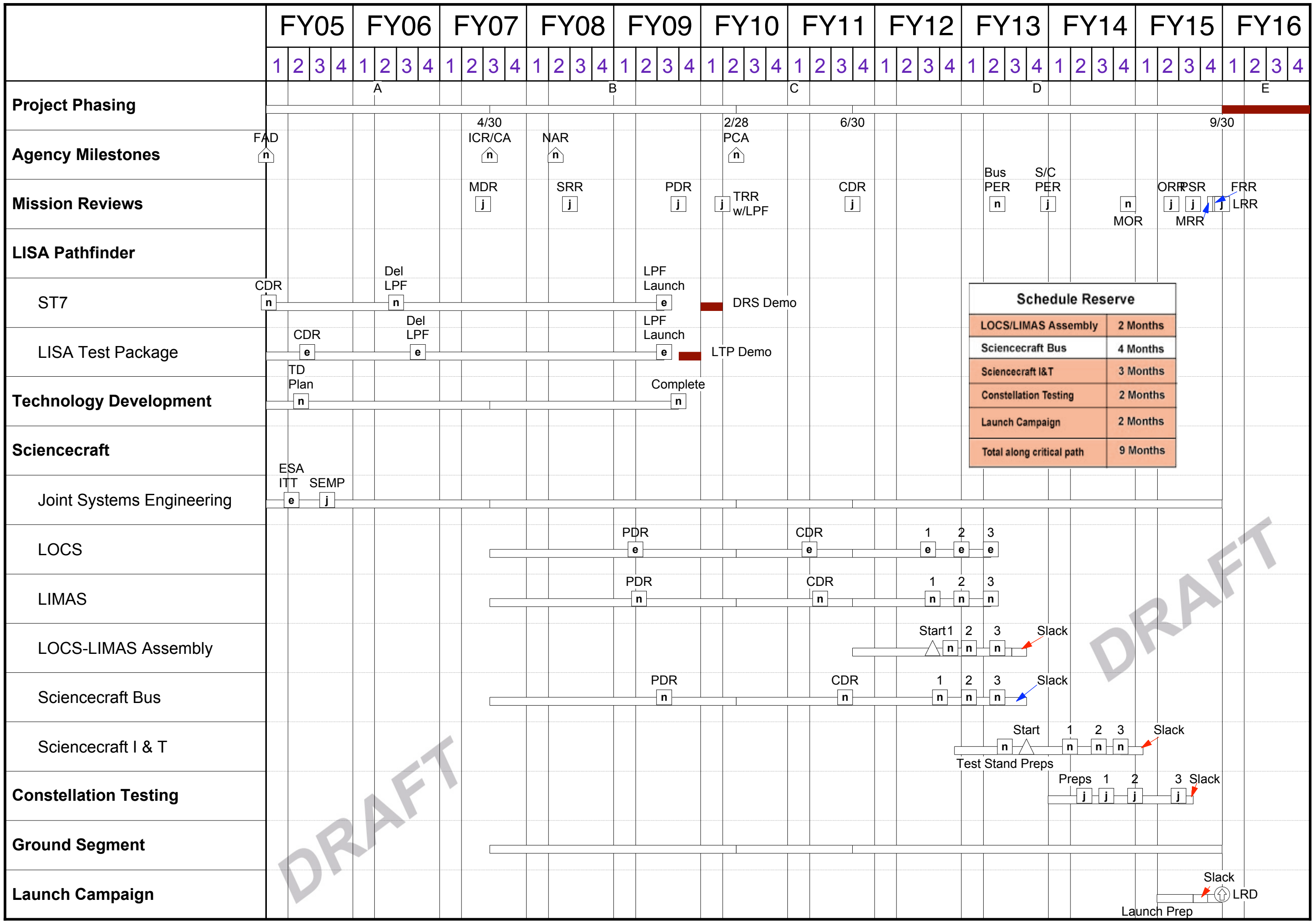
# LIGO CBE and Performance





# Master Schedule

Beyond Einstein: From the Big Bang to Black Holes




| Schedule Reserve | |
|---|---|
| LOCS/LIMAS Assembly | 2 Months |
| Sciencecraft Bus | 4 Months |
| Sciencecraft I&T | 3 Months |
| Constellation Testing | 2 Months |
| Launch Campaign | 2 Months |
| Total along critical path | 9 Months |